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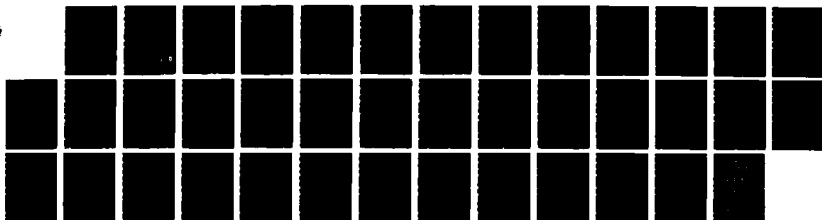
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Evaluation of Existing Bridge Maintenance Management Practices for Application to the Army

by
David M. Bailey
Lance R. Grenzeback

This report assesses current Army bridge maintenance management practices, reviews current practices in the public sector to identify existing and projected technology, and recommends methods and procedures to meet the Army's needs in this area.

A survey and telephone interviews were used to determine that the Army lacks standard procedures for establishing a sufficient inventory of its bridges, obtaining a minimum level of inspection, assessing bridge condition and level of required maintenance and repair, and prioritizing repair projects.

Based on the findings of the report, development of the following procedures derived from existing methods in the government and the public sector is proposed.

1. A bridge inventory procedure for storing and retrieving useful management information.
2. A uniform bridge inspection method which incorporates the Facilities Engineering Support Agency (FESA) Bridge Inspection Checklist.
3. A standardized Bridge Condition Index procedure for rating bridge condition and prioritizing bridge repair projects.

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FOREWORD

This research was conducted for the Office of the Assistant Chief of Engineers, Office of the Chief of Engineers (OCE) under Operations and Maintenance, Army Funding Document 86-0800017 dated January 1986, "Bridge Maintenance Management." The OCE Technical Monitor was Mr. Robert Williams (DAEN-ZCF-B).

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EVALUATION OF EXISTING BRIDGE MAINTENANCE MANAGEMENT PRACTICES FOR APPLICATION TO THE ARMY

1 INTRODUCTION

Background

The U. S. Army maintains about 1500 bridges (vehicle, pedestrian, and railroad), an approximate average of 10 bridges per installation. Many installations have no bridges on post and some installations have several, such as Fort Stewart which has 70 bridges (65 of these being wood vehicle bridges). A large number of the Army's bridges were built in the 1940's and 1950's, while some were built before the turn of the century. Because each installation may have its own unique mission, bridge traffic may vary considerably from installation to installation. For example, an installation which has tactical units may have a large amount of heavy, oversized equipment.

The Facilities Engineering and Housing Annual Summary of Operations report (The Redbook)¹ indicates that the Army spent \$13.6 million in 1985 maintaining these bridges. To assure that these funds are being used effectively and the mission is being supported, the Army must know the physical inventory and condition of its bridges and have the means to maintain them in a timely and cost effective manner.

Objectives

The objectives of this study are to:

1. Define technological and managerial problems related to Maintenance and Repair (M&R) of bridges on Army installations
2. Assess current Army bridge maintenance management practices
3. Assess the state of the art of bridge maintenance management in the public sector and investigate commercially available technology that can be implemented without further Research and Development (R&D)
4. Identify opportunities for improving Army bridge maintenance management
5. Recommend R&D for Army bridge maintenance management.

Approach

An extensive survey questionnaire was sent to all Army installation Directorates of Engineering and Housing (DEHs). Responses were received from 102 installations (Appendix A). In addition, telephone interviews were conducted with DEH personnel to

¹ *Facilities Engineering and Housing Annual Summary of Operations, FY 1985, Vol III Installation Performance (Office of the Assistant Chief of Engineers), For Official Use Only.*

obtain input about Army bridge maintenance management and associated problems. Existing literature was reviewed and leading practitioners and researchers at the federal, state, and county levels were surveyed to determine the state of the art and ongoing research in bridge maintenance management.

Mode of Technology Transfer

This report will be made available to the U.S. Army Pavements and Railroad Committee for determining required R&D in Army bridge maintenance management.

2 PROBLEM DEFINITION

The Army has approximately 1500 bridges on their installation property records. Seventy-five percent of these are vehicle bridges, 10 percent are pedestrian bridges and 15 percent are railway bridges. The Directorate of Engineering and Housing (DEH), which is responsible for maintaining the installation's entire real property, must also maintain the serviceability of its bridges. Because bridges are such a small portion of the real property, as compared to buildings and surfaced areas (roads, parking lots, and airfield runways), the DEH staffs generally do not have or need the skills, experience, or manpower to devote to bridge maintenance management.

The Army has a standard inventory procedure for bridges: the Integrated Facilities System (IFS). However, this procedure is part of the Army's Assets Accounting Module developed for work management and therefore does not include pertinent physical and historical bridge information needed by the DEH. Some installations do not use the IFS procedure. Also, the Army has no standard procedure for assessing the condition of its bridges. Therefore, it does not know accurately how many bridges it has, nor their location, condition, or age. The implication of this with respect to operational constraints, funding requirements, risk of catastrophic failure, and accident rates is significant.

While some larger Army installations have established bridge maintenance management programs, these have generally been ad hoc efforts. As a result, inventory, inspection, and maintenance records are compiled in differing formats and are often incomplete. No standard measure is provided for comparing bridge conditions at a given installation or between installations, or for comparing bridges with other facilities. Thus, there is no adequate means for assessing the bridge network's deficiencies and M&R requirements or performing any type of general prioritization for bridge projects.

3 CURRENT ARMY BRIDGE MAINTENANCE MANAGEMENT

Introduction

The Army's existing procedures for performing bridge maintenance management are in the areas of inventory, inspection, condition analysis, M&R analysis, and project prioritization and programming. These procedures are primarily manual and vary between installations. The following sections summarize how the Army performs these procedures.

Inventory

The Army's present bridge inventory (physical and historical information data base) is primarily accomplished by three methods:

1. Card index--real property information recorded on nonstandard cards
2. "As-built" records--blueprints, design plans, and drawings showing how the bridge was built
3. IFS system--automated inventory of a limited number of standard data elements.

The installations that use the card index method generally have few bridges. A card system is well suited to this type of situation, but often the type of data and the way it is recorded vary between installations. In addition, summarizing the data for planning and programming purposes can be very time consuming.

The "as-built" records provide fairly complete information. However, these records are very difficult to use for inventory purposes since the actual plans must be read by an engineer familiar with bridge design. They are also difficult to use in the development of any planning or programming schemes since large amounts of data not necessary to carry out these functions are included on the records. Also, as-built records do not lend themselves easily to the recording of historical data (e.g., last inspection date, design load, or load classification).

The IFS is the Army's existing system that uses a standardized method for the bridge inventory. This automated system provides a good starting point for a complete bridge inventory procedure but the data presently recorded are very limited. Data elements currently being stored are: design category code, facility number, deck area, bridge capacity (usually bridge length), year built, and condition code. Items such as bridge design, type of construction, location, load classification, number of lanes, and wearing surface are not recorded.

Some bridges have no records maintained on them. Bridges may have been built as training exercises and gradually became part of the bridge network through use. Others, which are older, have not had any work done on them and hence records were never created.

Inspection and Condition Analysis

The Army's current inspection requirements, as defined in AR 420-72,¹ are to conduct a detailed inspection of each bridge every year and to perform a revalidation of load carrying capacity every 3 years. The inspection and analysis is to be done by engineers qualified in bridge design, capacity, and characteristics.

However, there is no standard inspection procedure for determining the condition of a bridge other than the IFS component condition code which rates a bridge as being satisfactory (C-1), marginal (C-2), or unsatisfactory (C-3). The descriptions for each condition are very general and do not provide for separate evaluation of each bridge component (See Figure 1). This has led to a number of different methods of acquiring and analyzing data on bridge conditions.

At 80 percent of the surveyed installations, the annual inspections are performed either entirely or mostly by in-house personnel. The inspectors are usually engineers from either the Building and Grounds Division (B&G) or the Engineering, Plans, and Services Division (EP&S). Almost half these installations use the Facilities Engineering Support Agency (FESA) Bridge Inspection Checklist from the FESA *Bridge Inspection Brochure*,³ with the remaining installations using their own checklist or a modification of an existing FHWA/State inspection procedure. The other 20 percent of the installations contract out their annual inspections to Architect/Engineer (A/E) firms, resulting in a variety of different inspection procedures.

The triennial load carrying capacity analysis validations must be done by an engineer with a structural background. Standard procedures for determining the capacity of bridges are contained in TM 5-312, *Military Fixed Bridges*⁴ for military vehicle loadings, and the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Maintenance Inspection of Bridges*, 1983⁵ for AASHTO vehicle loadings. More than half the surveyed installations do not have the in-house capabilities to perform the analyses, requiring them to contract out to A/E firms or have FESA or the Districts provide this service.

FESA has circulated the *Bridge Inspection Brochure*, which includes guidance for inspecting the various types and sizes of bridges on Army installations. It provides a checklist for the visual inspection of each bridge component. Guide Specifications to assist the DEH in preparing contract documents for the annual and triennial bridge inspections are included in the brochure's appendixes. The brochure provides a good baseline for developing a standard bridge inspection procedure for the Army and this information is being included in a technical manual presently being prepared by FESA.

¹Army Regulation (AR) 420-72, *Surfaced Areas, Railroads, and Associated Structures* (Headquarters, Department of the Army [HQDA], Washington, DC, 24 March 1976).

³Tan, P. C. T., *Bridge Inspection Brochure* (U.S. Army Facilities Engineering Support Agency, May 1983).

⁴Technical Manual (TM) 5-312, *Military Fixed Bridges* (HQDA, Washington, DC, 1 December 1968).

⁵*Manual for Maintenance Inspection of Bridges*, 1983 (American Association of State Highway and Transportation Officials [AASHTO], 1984).

IFS COMPONENT CONDITION CRITERIA COMPONENT 17 - APPURTENANCES (BRIDGE APPURTENANCES)	
REFERENCES	DATE
ARs 420-72, 420-73, 420-76; TMs 5-624, 5-627, 5-632	1 May 1979
GENERAL DESCRIPTION	
<p>The appurtenances component includes signs, grade crossings, signals, guide posts, stop fences, traffic islands, manholes, headwalls, etc., associated with roads, railroads, airfields, and other stabilized areas. Appurtenances associated with land management include erosion and drainage control structures such as check dams, terraces, dikes, dams, flood gates, riprap, and the like. Appurtenances associated with agriculture outleaves include stock fencing, stock ponds, cattle guards, and corrals. Recreational facilities such as traps, bunkers, picnic equipment, and playing surfaces are included. Appurtenances associated with maintenance include irrigation systems, tree wells, and retaining wells. All types of grade separations/crossings are classified as bridges. A complete inspection should be made in the fall in preparation for winter, and another in the spring to determine the extent of maintenance and repairs needed. Bridge surface is considered part of road or walkway. At least one detailed inspection of each bridge will be made annually. Load carrying capacity analysis will be made at least triannually.</p>	
<p>CONDITION CODE C-1 Superstructure and substructure are in good condition with no structural defects. Steel in the superstructure is beginning to rust. Maintenance requirements include inspection, cleaning of roadway, drains, outlets, expansion joints, and spaces at the end of movable members; lubricating of roller, roller nests, rockers, shoes, bearing plates, sliding bearing, etc., plus painting of rusted areas; and sealing cracks in masonry.</p>	
<p>CONDITION CODE C-2 Superstructure is in good condition. Superstructure is beginning to deteriorate. Wood stringers are beginning to rot. Floor deck reflects excessive wear and is loose. Wheel guards are loose, split, and out of line. Trusses and handrails are out of line. Concrete decks are deteriorating. Stones are dislocated in masonry.</p>	
<p>CONDITION CODE C-3 Substructure is deteriorating. Superstructure may or may not be deteriorating. Compression members of truss are distorted. Timber piling or bent members are rotting. Substructure has collapsed or collapse is imminent. Restoration requirements include replacement of major components or complete bridge.</p>	

Figure 1. IFS component condition criteria for bridges. (From *IFS Real Property Maintenance Activities [RPMA] Module, Integrated Facilities System User's Manual Volume IV* [Department of the Army, Office of the Chief of Engineers, Washington, DC, 1 September 1979], p 3-D-17a.)

Maintenance and Repair Analysis

Maintenance and repair analysis is generally performed by either of two means, depending on the extent of M&R required. When an inspection determines the bridge to require minor repair and corrective maintenance, the DEH EP&S Division or Engineering Resources Management Division (ERMD) can determine the necessary work and develop the required work documents.

If the inspection determines that major repair and rehabilitation or replacement is required, a more complete and extensive condition analysis of the bridge is needed. This may be performed by the EP&S Division or, when in-house capabilities are insufficient, be contracted to an A/E firm. As part of these A/E services, a load carrying capacity analysis and M&R recommendations are usually provided. The EP&S division can develop the engineering plans and specifications for the project or have them prepared by the U.S. Army Engineer District or an A/E firm.

Project Prioritization and Programming

Because the number of bridges on an Army installation requiring M&R at one particular time would normally be very small, project prioritization and programming is not a major task. As stated earlier, an average installation has fewer than 10 bridges. Each bridge requires major repair work every 5 years or more. For those installations surveyed, the average Unconstrained Requirements Report amount for bridge M&R was \$76,000 and the average Backlog of Maintenance and Repair (BMAR) was \$32,000, with 90 percent of the installations having BMAR less than \$10,000 for their bridges. In essence, it is a matter of the DEH determining what bridges, if any, require M&R and getting the work programmed in the Annual Work Plan.

4 STATE OF THE ART--NETWORK LEVEL BRIDGE MANAGEMENT

Introduction

Network level bridge management systems are designed to manage limited amounts of data on a large number of bridges (for example, all interstate highway bridges in the state, all county bridges on a primary road system, or in the case of the Army, all bridges on an installation) and generate a general assessment of their current condition, M&R needs, and cost to maintain, rehabilitate, or replace. Network level bridge management systems are intended to support resource allocation decisions at the policy and planning level. Essentially, they are comprised of the following elements:

- data collection (inventory and inspection)
- condition analysis
- M&R analysis
- M&R costing
- project prioritization and programming.

Both the state of the art and the future outlook of each of these elements are discussed in this chapter.

Data Collection--Inventory and Inspection

Data must be collected to maintain an inventory of bridges and obtain information on their existing condition. This element of a bridge management system provides the raw information used to determine the M&R requirements and to prioritize and program projects.

Federal Requirements

All states are required by federal statute to maintain an inventory of the bridges within their jurisdiction. They must also inspect the bridges every 2 years. State and local regulations may require more frequent inspections, every year or 6 months, depending on the age and condition of the bridge. State bridge inventories and inspection data are reported to the Federal Highway Administration (FHWA) which compiles and maintains the National Bridge Inventory. This practice is relatively recent, being initiated in 1970.

Structure Inventory and Appraisal Form

The states use the FHWA's Structure Inventory and Appraisal Sheet (SI&A) to fulfill the federal inventory and inspection requirements (Figure 2). The SI&A records 89 items: 57 inventory items, 15 condition and appraisal items, and 17 items describing proposed renovations. The forms and procedures are described in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*.⁶

⁶*Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (U.S. Department of Transportation, Federal Highway Administration, January 1979).

Revised 12-70

Figure 2. Structure Inventory and Appraisal Sheet. (From *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* [U.S. Department of Transportation, Federal Highway Administration, January 1979], p 38.)

The SI&A is regarded as a good building block because it provides a basic, standard list of inventory and inspection information needed for bridge management, but lacks sufficient data on bridge components to support maintenance decisions. The sheet provides for a general condition rating of six elements of a bridge, including the three major components: deck, superstructure, and substructure (Figure 3). However it does not describe the condition of any of the individual subcomponents (e.g., expansion joints and wearing surface), and therefore must be augmented to be practical for state bridge management systems.

Inspection

The inspections, which provide input to the SI&A Sheet, are primarily visual inspections using standard methods and tools (e.g., tapes, feeler gauges, levels, and hammers). The level of effort varies with the frequency of inspection and the bridge condition, but usually involves a review of all major components of the bridge, measurement of critical components (to determine corrosion and wear), and preparation of a report documented with photographs and drawings. These inspections are supplemented by superficial inspections carried out by maintenance and road crews who are expected to check for obvious changes and deficiencies and report them.

Inspections are performed by bridge inspectors under the guidance of the district engineer. A few states, notably California, assign trained bridge engineers to do all inventory and inspections. A typical practice is for the state to use its own inspectors to inspect state bridges and employ consultants to inspect interstate highway and county bridges. All states have a bridge engineer and a staff of specialists at the state Department of Transportation (DOT) headquarters to assist the inspectors and the district engineers, and oversee the design and construction of new bridges.

Training

The states and counties rely on manuals, training films, and on-the-job training. Basic resources are the *Manual for Maintenance Inspection of Bridges, 1983* and the *Bridge Inspector's Training Manual*.⁷ Individual states have also developed training materials, films, and programs for specific bridge types and conditions.

Data Storage

In most states, SI&A data storage is automated, usually on a mainframe computer at the state DOT headquarters. Software for recording the inventory and inspection data is available from FHWA. Inspection records, drawings and other inventory materials are usually maintained at the district level. In some cases, this has led to redundant inventory and appraisal files: a formal, computerized (and often inaccurate) file at the state headquarters and an informal, manual (and often inaccessible) file at the district level.

Outlook

A number of states have or are planning to modify and expand the number of items on the SI&A Sheet to better serve their bridge management needs. The Pennsylvania Department of Transportation (PennDOT) has added 67 items to the SI&A and North Carolina DOT has added about 30 items. These additional items allow bridge inspectors

⁷*Bridge Inspectors Training Manual* (U.S. Department of Transportation, Federal Highway Administration, Corrected Reprint, 1979).

Rating	Description
N	Not applicable
9	New condition
8	Good condition--no repairs needed
7	Generally good condition--potential exists for minor maintenance
6	Fair condition--potential exists for major maintenance
5	Generally fair condition--potential exists for minor rehabilitation
4	Marginal condition--potential exists for major rehabilitation
3	Poor condition--repair or rehabilitation required immediately
2	Critical condition--the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete
1	Critical condition--facility is closed. Study should determine the feasibility for repair
0	Critical condition--facility is closed and is beyond repair

Figure 3. Condition rating scale for bridge elements in the SI&A Sheet.

to describe major components in more detail. For example, deck condition, a single item on the federal form, is expanded in the PennDOT form to include descriptions of the wearing surface, the expansion joints, the median barrier, the curbs and parapets, the railings, the sidewalks, and the drains/scuppers.

While software versions of the expanded state SI&A forms are available, these are usually tailored to individual state DOT management information systems. This makes it difficult to transfer the software directly to other users. The National Cooperative Highway Research Program (NCHRP) project will recommend that states shift their inventory and inspection data bases to IBM PC-compatible microcomputers and commercial data base software to make the systems directly accessible to bridge inspectors, maintenance engineers, and district engineers. Under this scheme, the basic inventory and inspection data would be maintained locally for project level bridge management, and a subset of the data would be extracted and uploaded for network level bridge management and federal reporting.

Condition Analysis

Condition analysis provides a systematic assessment of bridge conditions. This information can generally be used to determine what level of M&R is required.

Current Practice

Most states use the Federal Sufficiency Rating (FSR) or a variant of it as the analysis element of their network level bridge management system. The FSR is a weighted index, with a maximum rating of 100, representing the bridge condition. It is calculated using the inventory and inspection information collected on the SI&A Sheet. The index uses rules to vary the weight of factors in the following four areas (Figure 4):

1. Structural adequacy and safety (55 percent of rating, maximum)
2. Serviceability and functional obsolescence (30 percent of rating, maximum)
3. Essentiality for public use (15 percent of rating, maximum)
4. Special reductions, e.g., safety and detour impacts (13 percent of rating, maximum).

A given factor may be applied in more than one area. Detour length, for example, would be considered in both the essentiality for public use and the special reductions areas.

The index is stated as a value between 0 (totally insufficient) and 100 (totally sufficient). Under the FHWA's Highway Bridge Replacement and Rehabilitation Program (HBRRP) funding criteria, bridges with an FSR between 50 and 80 qualify for rehabilitation and bridges with an FSR of less than 50 qualify for replacement.

The major criticisms of the FSR are: (1) it is not reliable, and (2) it has a built-in bias favoring bridges built to interstate standards. Reliability depends heavily on bridge inspectors' assessments and, because SI&A sheets do not report the condition of individual bridge components, there is no way to ensure that the inspectors correctly or objectively evaluated the major components of the bridge. The FSR places considerable weight on high quality structural design and functional compatibility with the adjoining roadways because it was originally designed by FHWA to assess the condition of bridges

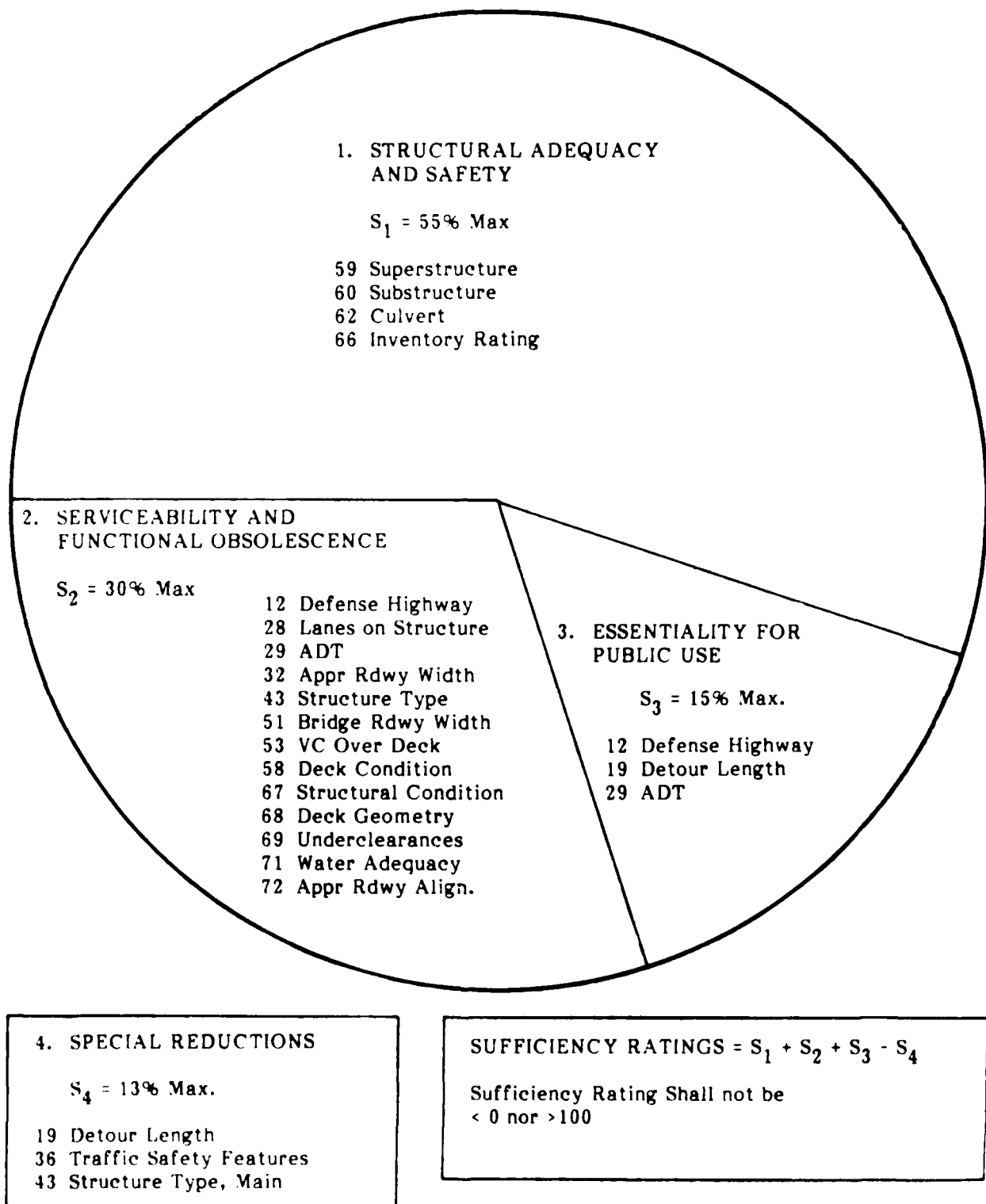


Figure 4. Summary of sufficiency rating factors. (From *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* [U.S. Department of Transportation, Federal Highway Administration, January 1979], p A-2.)

serving high-speed, high-volume interstate and primary highways. As a result, smaller bridges that are not built to interstate highway standards tend to receive a lower rating than may be warranted by their actual condition and use.

Outlook

To rectify these problems, states are modifying the FSR by adding items and changing the weighting schemes. PennDOT and North Carolina DOT employ different weighting schemes for different bridge and highway types. Several other states have devised separate indexes that use the same factors as the FSR, but use different scales or algorithms to calculate the sufficiency rating. For example, Minnesota DOT has replaced the FSR algorithms with a simplified system that assigns point values to major bridge components based on their condition and sums these to calculate an overall sufficiency rating.

More tailor-made indexes will be developed in the future. Since there is no consensus about what constitutes the "best" Bridge Condition Index (BCI), agencies are tempted to design their own indexes. The selection of factors to be included in an index is highly judgmental and reflects not only different engineering approaches to bridge maintenance, but also different policy and program objectives. An agency concerned with the public's perception of bridge conditions may choose to give greater weight to deck conditions and deck maintenance, while an agency trying to minimize the total economic cost of bridge maintenance may give greater weight to structural conditions and pay less attention to potholes in the deck. With the automation of inventory and inspection data, it will be easier for state and county maintenance engineers to construct specific and detailed condition indexes and use these at the network level.

Maintenance and Repair Analysis

Once the condition of a bridge is determined, general M&R alternatives can be determined.

Current Practice

Although the intent is otherwise, most states consider only one action in their network level bridge management systems. This is usually the action recommended and reported on the SI&A Sheet; for example, rehabilitation or replacement to bring a bridge up to standards. Bridges that do not require major action are generally slated for routine maintenance.

These practices weaken the function of a network level bridge management system, which is to give administrators and engineers greater flexibility in making tradeoffs between bridge safety, bridge performance, and bridge costs. Current systems can determine the cost of bringing the bridges in the state or district up to new construction standards (i.e., to a maximum level of service), but cannot determine what mix of maintenance actions will yield the highest level of service for the network at a given funding level.

Outlook

The solution, toward which some states are working, is to generate a range of alternative maintenance actions for each bridge and make some or all available for

consideration in planning decisions. Several states, including Pennsylvania, have suggested that at least two maintenance actions be defined as a matter of form:

1. A maximum maintenance alternative (e.g., rehabilitation or replacement) that would bring the bridge up to full service standards)

2. minimum maintenance alternative (e.g., posting and emergency corrective maintenance) that would preserve public safety.

While this is not considered an ideal solution, it puts bounds on the maintenance choices and makes possible a crude tradeoff analysis between service levels and maintenance investment.

Maintenance and Repair Costing

Cost estimates are required for each M&R alternative to enable the manager to select the best strategies using life cycle costing or some other type of analysis.

Current Practice

State bridge management systems use the M&R cost estimates provided by district bridge inspectors and engineers on the SI&A Sheet. The accuracy and reliability of these cost estimates vary greatly depending on the experience of the inspector, the bridge type, and its location. The FHWA collects and reports bridge replacement cost data by state. Cost estimates for rehabilitation are also reported, but are less reliable due to limited data.

These cost estimates are usually restricted to initial capital costs. Life cycle costs are seldom used and cost estimates for routine preventive and corrective maintenance are generally not assigned to individual bridges. Wisconsin is one of the few states that uses estimated life cycle cost data in its network level bridge management system.

Outlook

Most states have developed or are planning to develop cost accounting software that permits them to track highway pavement maintenance costs. Some have extended these systems to track bridge maintenance costs, which will be used to generate historical and current cost data. The first objective will be to refine capital cost estimates and determine the proper allocation of corrective and preventive maintenance costs.

Project Prioritization and Programming

Prioritization and programming determine how maintenance resources should be allocated among the network's bridges to maximize benefits to the road users, the agency, and the public.

Current Practice

Current practice is generally limited to rank ordering of bridges using the Federal Sufficiency Rating or the state version of the FSR. Most states have automated this process, allowing them to sort and rank order by highway system designation, bridge type, and district. Since prioritization and programming within funding categories are

major administrative concerns for state DOTs, they become major time-consuming activities.

Prioritization and programming decisions are driven by three factors:

1. **Safety:** a paramount concern for most state DOTs since many bridges are *undermaintained* and the consequences of bridge failure, which include legal and political liability, are severe
2. **User Costs:** generally measured by the public's perception of ride comfort
3. **Economics:** where possible, maintenance actions that will significantly extend the remaining life of a bridge are given priority over shorter life investments.

Very few (if any) states and counties rely entirely on numerical rankings for their programming decisions. Most use the rankings only as a starting point and then rely heavily on the judgment of district and state bridge engineers with substantial advice from political administrators and local officials. Some states use informal decision rules to speed up the evaluation process. For example, if the cost of repair approaches x percent of the cost of replacement, then replace rather than repair; if major repairs extend the remaining life of the bridge by x years, they are cost justified. Most regard the current techniques as adequate given the lack of detailed and reliable data.

This practice is relatively subjective, can be very time-consuming, and does not provide much assistance in optimizing maintenance investments. State DOT political administrators and managers would like to apply more sophisticated techniques, such as life cycle costing, calculation of present worth, and linear programming optimization routines, but are skeptical about the effectiveness of such techniques.

Outlook

State DOTs will devote their primary attention to improving BCIs (the FSR and variants of it) and will continue to rely on sorting and rank ordering techniques to assist the prioritization and programming process.

As more sophisticated prioritization and programming tools are developed for highway pavement maintenance management programs, states will try to transfer these to bridge maintenance management. NCHRP Project 12-28(2) is to develop a framework for a bridge management system and identify appropriate methods and techniques (Appendix B). However, the NCHRP 12-28(2) draft interim report concludes that better data is needed before more sophisticated prioritization and programming techniques can be used for bridge management systems.

Summary

Procedures for creating and maintaining bridge inventories, carrying out bridge inspections, and analyzing bridge conditions are reasonably well developed. However, procedures for estimating maintenance costs are only adequate. Prioritization and programming techniques at the network level are generally limited to indexing, weighting, and ranking schemes. These techniques are rudimentary, but judged adequate by practitioners, since most state bridge management programs are operated in a "crisis mode" that eliminates the need for more sophisticated long-term programming.

5 STATE OF THE ART—PROJECT LEVEL BRIDGE MANAGEMENT

Introduction

Project level bridge management systems are intended to manage specific data about one bridge, to generate a detailed evaluation of its condition, and assess the impact of alternative maintenance actions on load carrying capacity, deterioration rate, remaining life, and life cycle economic cost. These systems should support network level resource allocation decisions.

There are major gaps in the present state of knowledge about bridge maintenance that have precluded the rapid development of sophisticated project level bridge management systems. These include:

- Lack of knowledge of the structural behavior of bridges over time (e.g., deterioration rates)
- Lack of economic and engineering criteria to guide the design, selection, and implementation of maintenance actions
- Lack of precise maintenance costs
- Lack of knowledge about the long-term cost-effectiveness of maintenance actions.

A project level bridge management system should include the following elements:

- data collection (inspection)
- condition analysis (structural capacity)
- M&R alternatives
- M&R costing.

The state of the art and future outlook of each of these elements are discussed below.

Data Collection—Inspection

A project analysis requires detailed information on the condition of a bridge's components. These data are used for assessment of the structural capacity of the bridge, estimation of its remaining life, and selection of M&R strategies.

Current Practice

Data collection for project level bridge management systems begins with the inventory and inspection work performed at the network level, but gives more attention to direct measurement and complete documentation of corroded or damaged structural components. In cases where the data do not provide conclusive information, or where serious deterioration is detected, the bridge engineer may elect to undertake more sophisticated field and laboratory tests.

The tests are designed to determine the local condition of materials and the behavior of the bridge and individual components under load. Concrete cores and steel samples may be analyzed for strength, corrosion, and cracks. Wires and cables are checked for failures and the paint thickness is measured. Field instrumentation may be applied to detect movement and strain in the structure and measure component forces and pressures. Special expertise is required to conduct such tests and evaluate the results. Some states have the trained personnel on staff, but most contract these services from consultants.

There is extensive technical literature on materials and structural testing techniques, but no standard reference manual on conducting and interpreting test procedures exists for bridges. Some states have developed guidelines for their own use.

The complexity and level of effort required to perform a specialized inspection effectively limits its use to a few critical bridges which have obvious and dangerous deterioration. States seldom have the opportunity to inspect more than a small percentage of their bridges in any detail. As a consequence, they have little information to support the development of alternative M&R actions for these bridges, and insufficient historical data to analyze the cost effectiveness of maintenance.

Outlook

There is substantial ongoing technical research on bridges, but much of it concerns techniques and materials for new construction. Relatively little research is focused exclusively on the problems of maintenance, restoration, and rehabilitation of existing bridges. The Strategic Highway Research Program, for example, has proposed four research projects dealing with methods to prevent the deterioration of concrete in bridges and pavements. Within the maintenance area, there is considerable interest in development of nondestructive methods for testing the condition of concrete bridge decks because of their visibility to the public. The public can easily see and feel deck deterioration (e.g., potholes or ruts).

Condition Analysis—Structural Capacity

Determining the structural capacity of a bridge is necessary to assess its structural condition, the allowable traffic load, and the impact of M&R alternatives.

Current Practice

To calculate the structural capacity of a bridge, state bridge engineers rely primarily on design calculations documented in *Standard Specifications for Highway Bridges*.⁸ However, the design standards do not provide detail on the treatment of deteriorated components. The *Manual for Maintenance Inspection of Bridges*, 1983 is used to estimate the effects of corrosion and spalling, but proper calculation of the structural capacity of deteriorated bridges remains up to the professional judgment of trained bridge engineers.

Many of the calculation routines have been automated. Several hundred software programs are available to analyze bridge and component performance. These individual programs usually cover only one or two types of bridges. The most extensively used

⁸*Standard Specifications for Highway Bridges*, 13th edition (AASHTO, 1983).

program is the Bridge Analysis and Rating System (BARS) developed for AASHTO. The software is proprietary and can be purchased or leased through AASHTO. Twenty-four states currently participate in the BARS user group.

BARS will calculate the load factor rating (LFR) for bridges. However, the calculation requires development of a digitized data base describing the structure and materials of the bridge. Software to digitize engineering drawings is commercially available or the service can be purchased from consultants. (PennDOT recently spent over \$12 million to prepare a digitized data base of its bridges.) Once the data base is developed, it can be archived and updated to reflect deterioration reported by inspections and repairs made by M&R crews. The BARS program is menu-driven and can be used by district engineers without extensive training.

Other similar programs are available through FHWA and state DOTs. For example, Wyoming DOT has developed a program to calculate the working stress of bridges (BRASS program) and Arizona DOT has developed a program to analyze prestressed concrete bridge members.

Outlook

State DOTs plan to expand their use of automated analysis software as better data bases become available. For example, PennDOT plans to use its data base and structural analysis programs to process and check requests for overweight load permits and routes.

Maintenance and Repair Analysis

Once a bridge has been inspected and its condition analyzed, M&R alternatives can be generated.

Current Practice

At the project level, most states consider but do not necessarily analyze nor document the following:

- Actions affecting bridge service capacity
- No action
- Preventive maintenance
- Corrective maintenance
- Rehabilitation (restoration, widening, and strengthening)
- Replacement (new construction) (Preventive and corrective maintenance are considered maintenance proper, but rehabilitation and replacement are treated as maintenance management alternatives.)
- Actions affecting bridge usage
- Closure
- Restrictive posting (weight limits, speed limits, and number of open lanes).

Most states focus attention on rehabilitation and replacement alternatives since federal funds are available for these actions if the bridges qualify under the HBRRP. When funding is not available, no action is taken for new bridges that do not yet demand maintenance effort, and restrictive posting is used for bridges with significant deficiencies that do not pose immediate safety risks.

Few states and counties analyze more than two options--restoration or restrictive closure. Preventive and corrective maintenance alternatives are not costed out per bridge by many states, making it difficult to treat them as alternatives in economic and programming models.

Outlook

It has been recognized that limiting the number of alternatives defined at the outset of a project results in limited ability to optimize maintenance investments. In addition to defining alternatives as a matter of form (e.g., action needed to bring the bridge up to standards, and action needed to maintain public safety), bridge engineers are developing decision tree models (Figure 5). The models define appropriate M&R actions based on bridge condition.

Researchers are exploring the development of expert systems that would computerize these decision models, permitting development of more sophisticated and interactive models. Work on expert systems at the Massachusetts Institute of Technology shows considerable promise for the future. While potentially a very powerful tool, work on computerized expert systems for bridge maintenance is just beginning and will ultimately be hampered by the lack of data and knowledge about the structural behavior of bridges and the effectiveness of maintenance.

Maintenance and Repair Costing

Selection of the optimum M&R strategy can be achieved by performing some type of economic analysis. To do this, costs for the proposed M&R actions must be estimated.

Current Practice

Many states lump all maintenance costs into very few categories in their cost accounting systems. Although cost accounting practices vary by type of contract and funding agency, bridge maintenance work and costs accrued by contractors are generally well documented in reports and invoices, while work and costs accrued by in-house maintenance and engineering staffs are not. Similarly, work and costs accrued for new construction are usually well accounted, while M&R records for existing bridges are very incomplete.

States lack the data and, therefore, the capability to track historical costs and project trends. This precludes the development of valid and reliable life cycle cost data and effective use of economic analysis techniques, such as present worth analysis.

Element	Consideration	Attribute	Causes	Condition	Severity	Maintenance Option
Wearing surface	Safety	Percent Change in the number of accidents	Roughness	Rutting	Less than 1/2 in.	1. Skin patch 2. Grind surface 3. Overlay 4. Do nothing
					1/2 to 1 in. deep	1. Skin patch 2. Grind surface 3. Overlay
				Localized depressions	Over 1 in. deep	1. Grind surface 2. Overlay
					Depressions less than 1 in. deep and 1 ft sq <10% of surface area	1. Patch 2. Skin patch 3. Do nothing
					10 to 25% of surface area	1. Patch 2. Skin patch 3. Overlay
			Slippery surface	Surface bleeding	25% or more of surface area	1. Skin patch 2. Overlay
					<10% of surface area	1. Sand 2. Do nothing
					10 to 25% of surface area	1. Sand 2. Overlay 3. Do nothing
					Over 25% of surface area	1. Sand 2. Overlay
				Aggregate polishing	Slight, <10% of wheel paths	1. Grind surface 2. Overlay 3. Do nothing
					Moderate, 10 to 25% of wheel paths	1. Grind surface 2. Overlay
					Heavy, 25% of wheel paths	1. Grind surface 2. Overlay

Figure 5. Decision tree for maintenance action—bridge wearing surface. (From Byrd, Tallamy, MacDonald and Lewis, *Concept Study for an Army Bridge Maintenance Management System: Final Report* [Prepared for the U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois, August 1985], pp 2-8.)

Outlook

The paucity of bridge cost data and the weakness of many state DOT cost accounting systems is a result of institutional problems (lack of money and lack of innovation), not a technical problem. Data base and accounting software is available to handle bridge M&R costing data. Improvements in this area will be driven by the amount of funding available to upgrade data base and accounting systems.

Summary

In the public sector, project level bridge management systems are not as well developed as network level bridge management systems and comparable project level pavement management systems. Few states have formal systems that are readily distinguishable from the activities that make up the more encompassing network level systems.

There is extensive technical literature on all aspects of bridge design and maintenance, and there is ongoing R&D to improve the state of the art in bridge maintenance management at the project level, but there is no expectation within the industry that these will lead to major state of the art improvements in the near future. Project level bridge maintenance management is still regarded as an art and is likely to remain so for some time.

6 TECHNOLOGICAL OPPORTUNITIES

The state of the art exists to develop inventory, inspection, and condition evaluation procedures for network level management (installation, Major Command [MACOM], Office of the Chief of Engineers [OCE]) of the Army's bridges. In comparison, project level analysis state of the art is not nearly as well developed and would require extensive R&D efforts to advance the state of knowledge of bridge maintenance.

Based on the input from potential users and a review of the current bridge maintenance management practice, procedures have been proposed to provide the DEH with the information needed to establish an inventory of installation bridges, obtain a minimum level of inspection, assess bridge condition, and provide a generalized prioritization for bridge M&R. Such procedures allow the DEH, as well as upper management, to determine overall maintenance requirements and program and direction needs. To do this, the procedures must be designed to address situations unique to the Army's bridge network and must fit into the DEH's present operations.

Specifically, the three procedures are:

1. An inventory procedure and data base for collecting and managing information (physical and historical) on the installation's bridges
2. A standard bridge inspection procedure that will not place unrealistic demands on the installation's resources
3. A generalized condition rating procedure and indexing system that will help the DEH set priorities for M&R projects at the network level.

The following paragraphs discuss each procedure and analyze its potential for being accomplished by existing technology.

Inventory

An inventory data base for bridge information can be created to store and retrieve bridge related data. Development of the data base and selection of the data elements can be accomplished using the SI&A sheet as a basic building block. Items of little use to the Army could be eliminated and items unique to the Army could be added (i.e., design category code, military design load, and military load classification). The three key fields for IFS (Installation Number, Facility Number and Facility Suffix) should be included to ensure the interface with the IFS system. This inventory should be maintained at the installation level in manual files or a microcomputer data base, making all information readily available to the DEH. An automated system could generate reports which would supply useful management information.

Inspection

A standard inspection procedure using the FESA inspection checklist is being developed and will be included in a FESA Technical Manual. Minor modifications are required to provide feedback on general M&R requirements and priorities. This procedure could be used (and possibly required) for detailed inspections accomplished in-house and serve as a requirement for inspections performed by A/E firms. This would

assure a minimum level of inspection and eliminate informational differences which presently occur among installations and sometimes even between bridges at an installation.

This inspection procedure, along with inspector training, will provide a good condition assessment of bridge condition and level of needed M&R, and signal which bridges require a more in-depth engineering analysis.

Condition Rating

A bridge condition rating procedure can be developed which would quantify the inspection results into a standard BCI. Based on a scale of 0 to 100, the BCI would rate the bridge with respect to its level of M&R requirements.

As an analysis tool for network level management, the FSR is regarded as a good building block, but one that needs enhancement if it is to be objective. A more appropriate rating scheme for the Army would be based on the structural adequacy of the major bridge components (deck, superstructure, and substructure) and not on the structural design and functional compatibility with the adjoining roadways. The modified FSR algorithms derived by some of the different states should be evaluated for this purpose.

The resulting BCI would provide the DEH with the means to evaluate the overall condition of the installation's bridge network, determine general levels of M&R, and invoke project prioritization schemes.

7 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This investigation noted the following three areas related to bridge maintenance management at Army installations which need improvement:

1. Installations do not have an accurate and complete inventory of their bridges to aid in planning and programming of bridge M&R
2. The Army has no standard inspection procedure to provide a uniform evaluation of bridge condition
3. The DEH lacks an analytical, objective process for assessing the condition of its bridge network and setting priorities for repair projects.

Recommendations

A review of current Army bridge maintenance management practices and assessment of the state of the art of bridge maintenance management in the public sector reveal that the Army's needs could be met with R&D in the following four areas:

1. Development of an inventory procedure for storing and retrieving useful management information
2. Development of a uniform inspection method, incorporating an enhancement of the FESA Bridge Inspection Checklist, to provide an assessment of the structural condition of the bridges and an indication of the required level of M&R
3. Development of a BCI to provide a uniform method of rating bridge conditions and prioritizing repair projects
4. Development of a microcomputer-based inventory and inspection data base at the installation level.

All of these procedures exist in reasonable form in the government and the public sector and are adaptable for use by the DEHs after modification to meet the Army's needs. The Army will be able to draw upon examples and experiences from several states. Therefore, it is recommended that these procedures be developed to assist the DEH in performing its Real Property Maintenance Activities mission and assure serviceability of its bridges.

Bridge maintenance management at the project level is not well developed and will require extensive R&D to advance the state of the art. It is also recognized that almost all types of facilities need some level of maintenance management. However, the Army's management needs for bridges, as compared to roads, buildings, and roofs is limited because of the size of the inventory, low yearly required M&R, and low level of BMAR. Therefore, the benefits realized by the Army in developing project level bridge maintenance management techniques may not justify the effort required to achieve them. It is not recommended that the Army pursue extensive R&D in this particular area at this time.

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**APPENDIX A: MILITARY INSTALLATIONS RESPONDING TO SURVEY
FOR CURRENT ARMY BRIDGE MAINTENANCE MANAGEMENT**

ANNISTON ARMY DEPOT
ANSBACH MILITARY COMMUNITY
ASCHAFFENBURG MILITARY COMMUNITY
AUGSBURG MILITARY COMMUNITY
BAD KREUZNACH MILITARY COMMUNITY
BAD TOELZ MILITARY COMMUNITY
BAMBERG MILITARY COMMUNITY
BAUMHOLDER MILITARY COMMUNITY
BAYONNE MILITARY OCEAN TERMINAL
BERCHTESGADEN SUB MILITARY COMMUNITY
BERLIN MILITARY COMMUNITY
CAMP EDERLE
CAMP ZAMA
CORNHUSKER ARMY AMMUNITION
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FORT ORD
FORT POLK
FORT RICHARDSON
FORT RILEY
FORT RUCKER
FORT SHAFTER
FORT SHERIDAN
FORT SILL
FORT STEWART
FORT WAINWRIGHT
FORT WHITTIER
FRANKFURT MILITARY COMMUNITY

FULDA MILITARY COMMUNITY
GIESSEN MILITARY COMMUNITY
GOEPFINGEN MILITARY COMMUNITY
HANAU MILITARY COMMUNITY
HARRY DIAMOND LABS
HEIDELBURG MILITARY COMMUNITY
HEILBRONN MILITARY COMMUNITY
HOHENFELS TRAINING AREA
HOLSTON ARMY AMMUNITION PLANT
INDIANA ARMY AMMUNITION PLANT
IOWA ARMY AMMUNITION PLANT
JEFFERSON PROVING GROUNDS
JOLIET ARMY AMMUNITION PLANT
KANSAS ARMY AMMUNITION PLANT
LAKE CITY ARMY AMMUNITION PLANT
LEXINGTON-BLUEGRASS ARMY DEPOT
LIMA ARMY TANK PLANT
LONGHORN ARMY AMMUNITION PLANT
MAINZ MILITARY COMMUNITY
MCALISTER ARMY AMMUNITION PLANT
MILAN ARMY AMMUNITION PLANT
MUNICH MILITARY COMMUNITY
NEU ULM MILITARY COMMUNITY
NEW CUMBERLAND ARMY DEPOT
NEWPORT ARMY AMMUNITION PLANT
NUERNBURG MILITARY COMMUNITY
OAKLAND ARMY BASE
PICATINNY ARSENAL
PINE BLUFF ARSENAL
PRESIDIO OF SAN FRANCISCO
RADFORD ARMY AMMUNITION PLANT
RAVENNA ARMY AMMUNITION PLANT
REDSTONE ARSENAL
ROCK ISLAND ARSENAL
ROCKY MOUNTAIN ARSENAL
SACRAMENTO ARMY DEPOT
SAVANNA ARMY DEPOT
SCHWEINFURT MILITARY COMMUNITY
ST LOUIS AREA SUPPORT CENTER
STUTTGART MILITARY COMMUNITY
SUNFLOWER ARMY AMMUNITION
SUNNY POINT MILITARY OCEAN TERMINAL
TOBYHANNA ARMY DEPOT
TOOELE ARMY DEPOT
VOLUNTEER ARMY AMMUNITION
WALTER REED ARMY MEDICAL CENTER
WEISBADEN MILITARY COMMUNITY
WEST POINT MILITARY ACADEMY
WILDFLECKEN MILITARY COMMUNITY
WUERZBURG MILITARY COMMUNITY
YUMA PROVING GROUND

APPENDIX B: RESEARCH AND TECHNOLOGY

Current and planned research will address some of the needs in the area of bridge management. Much of this research will be administered by the NCHRP under contract to AASHTO. The research will draw upon the FHWA and state DOTs for funding. NCHRP is a program within the Transportation Research Board, which is a part of the National Research Council of the National Academy of Sciences. A few states and universities are also conducting research in bridge management.

This current research fall into two categories: bridge management and bridge service capacity. Short descriptions of some of these projects are provided in this section.

Bridge Management Research

Bridge Management Systems (NCHRP Project 12-28[2])

The objective of this research is to develop a network level bridge management system. The project is to review domestic and foreign bridge management practices, establish a logical framework for a bridge management system, determine the application of computers and software to bridge management, and then develop a model bridge management system. The project has been underway for a year and an interim report is near completion.

The bridge management system is expected to provide:

- Methods of assessing present and future needs of existing bridges
- Guidelines for determining cost-effective alternatives both with and without financial constraints
- Priority treatment of needs through the use of generalized work activities
- Flexibility to accommodate a variety of policy approaches
- Flexibility to accommodate future expansion to the project level
- Methods to ascertain standards of data reliability.

Pennsylvania Bridge Management System

Pennsylvania DOT has an ongoing research program to develop, test, and implement a total bridge management system. PennDOT is drawing upon Highway Planning and Research funding to develop the program. The general objective of the work is to develop a management tool that will enable a systematic determination of present and future needs for maintenance, rehabilitation, and replacement of bridges in Pennsylvania under various scenarios, and provide guidance in the effective use of designated funds.

The project will build upon PennDOT's Structure Inventory Records System (SIRS), an expanded version of the FHWA SI&A form, and incorporate some of the work done by the North Carolina DOT and Dr. David Johnston at North Carolina State University on performance requirements for low-volume bridges. The PennDOT bridge management

system has been designed and a software contractor is being hired to develop the data base software. The system is scheduled for completion in April 1987.

Bridge Service Capacity Research

Several research projects will attempt to improve the state of knowledge of the structural behavior of bridges. If successful, this research will make it possible to more accurately assess the value of M&R actions; however, much of this research will be directed toward understanding the structural behavior of large, complex bridge structures and may not be immediately applicable to low volume bridges.

Nondestructive Load Testing in the Bridge Evaluation and Rating Process (NCHRP 12-28[13])

The objective of this project is to develop nondestructive physical tests that can be used on an existing bridge to provide detailed information about the effect of joints, multiple load paths, nonlinearities, friction, and other factors on the bridge's service capacity. These test data would enable the development of exact analog models of the bridge, which could then be used to estimate the long-term effects of M&R actions. This would, in turn, make it possible to evaluate and rate bridges on the basis of their actual condition, relying less on the judgment of bridge inspectors or idealized mathematical models.

Inelastic Rating Procedures for Steel Bending Members with Full or Partial Continuity (NCHRP 12-28[12])

The objective of this project is to develop criteria for the inelastic (plastic) rating of existing steel bridges with full or partial continuity among bridge members. Present rating methods are based on assumptions of elastic behavior and may underestimate the true strength of bridges.

Fatigue Behavior of Welded and Mechanical Splices in Reinforcing Steel (NCHRP 10-35)

The objective of this project is to provide bridge engineers with better guidelines on the behavior of reinforcing bar splices, which are often used in repairing, widening and renovating existing reinforced concrete bridges.

Hydraulic Analysis of Bridges on Streams with Moveable Beds and Banks (NCHRP 15-11)

It is estimated that 85 percent of bridges in the National Bridge Inventory are constructed over waterways and subject to erosion during floods. The objective of this project is to develop models allowing bridge maintenance engineers to predict erosion patterns and assess design and maintenance countermeasures.

Bridge Service Requirements Research

In parallel with the research on bridge structural performance are a number of projects designed to better understand the loads that bridges are required to carry. The focus of this research is on loads created by heavy trucks. The research on highway pavement impacts is directly applicable to bridge deck maintenance and indirectly to bridge structural analysis.

Development of Bridge Load Spectra for Rating (NCHRP 12-28[11])

Current service requirements are very general and often conservatively high, resulting in higher construction and maintenance investment than may be warranted by actual traffic and loads. The objective of this research is to develop service requirements that more accurately reflect actual traffic and loads on existing bridges.

Development of Low-Cost Bridge Weigh-in-Motion System (NCHRP 3-36)

The objective of this project is to develop a low-cost system of sensors (axle sensors and strain transducers), signal electronics, and data processing software that can be mounted on an existing bridge to weight trucks as they pass over the bridge.

Effects of Truck Sizes and Axle Configurations on Pavement and Performance (NCHRP 1-25)

Recent changes in legal truck sizes, tire pressures, and axle configurations have raised concerns about the adequacy of traditional pavement and bridge design guidelines. The objective of this project is to assess and demonstrate the impact of these changes on pavements and bridges, evaluate vehicle configurations, and recommend approaches to the redesign of vehicles that will lessen the impacts of increasing loads.

Relationships Between Vehicle Configurations and Pavement and Bridge Design (NCHRP 2-16)

The objectives of this research are to explore the impact of longer trucks with more axles and lower axle loads on pavements and bridges, systematically explore the relationship between vehicle configuration and pavement and bridge designs, and recommend the more effective combinations for a practical and efficient national highway transportation system.

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